

DATA COMPRESSION FOR NEAR EARTH AND DEEP SPACE TO EARTH
TRANSMISSION p-6

Daniel E. Erickson
Jet Propulsion Laboratory
Pasadena, CA 91109

1. The Applications

1.1 Near Earth Satellites

Communications Capabilities: In the foreseeable future, near Earth polar and equatorial satellites will communicate to the ground via the Telemetry and Data Relay Satellite System and its successors. TDRS can support up to 300 megabits per second of dedicated transmission. Contention for this high-rate communication resource will limit access by any one satellite. The TDRS also has several lower rate channels which can allow access by multiple satellites. Data may also be dumped at high rate to Ground Tracking and Data Relay Stations as the satellite passes through their range. Some satellites may also support direct downlink of timely local data to small ground stations. Direct downlink transmission will be at data rates of only a few megabits per second, to allow small inexpensive receiving stations.

Communications Drivers: Several instruments which have been considered for Earth Observation have high raw data rates. The Synthetic Aperture Radar (SAR) instrument takes data at over 300 megabits per second. The High Resolution Imaging Spectrometer (HIRIS) instrument takes data at 420 megabits per second. Of additional concern are instruments with lower data rates but high data volumes because of high duty cycles. The Moderate Resolution Imaging Spectrometer (MODIS) instrument, for instance, takes data at 20 megabits per second continuously. Uncompressed, the MODIS data would take 40% of the average Earth Observing System (EOS) platform total downlink volume. Near real time direct downlink data are desired for ice data for navigation purposes, for regional pollution, rainfall and crop data, and remote sensing data for field experiments.

1.2 Spacelab & Space Station Freedom

Communications Capabilities: The space station Freedom will communicate with Earth at 50 megabits per second.

Communications Drivers: Potentially, the most data intensive activities related to the space station will be remote operation of scientific experiments. In this operating mode, sometimes called *telepresence*, principal investigators on the ground observe the progress of space based experiments and direct them either through electronic commands or through voice communication with the astronauts. In order to direct the experiment, the P. I. needs information on the progress of the experiment, possibly through real time video. Full color video, uncompressed would take 46 megabits per second per video channel. Remote monitoring is desirable for microgravity and life sciences experiments. In addition, microgravity experiments may require non real time high resolution, high rate video to meet science objectives.

1.3 Geostationary Platforms

Communications Capabilities: Geostationary platforms would probably communicate directly with ground stations. They might even act as relays for satellites in low earth orbit. Several communications options could be available in the first decade of the twenty first century when the geostationary platforms are planned. Optical communications with spatial diversity to reduce the intervals of

blockage due to weather could achieve rates on the order of a gigabit per second. Near real time direct downlink to field sites would still have significantly constrained communication rates.

Communications Drivers: Geostationary Earth observation platforms will tend to have staring instruments with wide, continuous coverage. These will be based on EOS instruments and may be capable of very high data rates.

1.4 Lunar Base

Communications Capabilities: Bases on the near side of the moon will communicate directly to ground stations on Earth or with Earth orbiting relay satellites.

Communications Drivers: A lunar base would conduct experiments, explore the lunar surface, and make astronomical observations. The experiments and exploration would benefit from telepresence. The observations may have very high raw data rates.

1.5 Deep Space

Communications Capabilities: The data rates from interplanetary spacecraft are limited by spacecraft and ground based antenna size and constrained spacecraft transmission power. The highest data rate planned for the Galileo Spacecraft at Jupiter is 134 kilobits per second. Missions such as a Neptune orbiter face even lower data rates unless new technologies such as optical communications can be developed. With optical communications, rates on the order of a megabit per second can be hoped for.

Communications Drivers: Imaging has put the highest demand on downlink resources in recent missions. As we move to more detailed studies of the planets, moons, asteroids, and comets of our solar system, multispectral imaging and synthetic aperture radar, both data intensive instruments, will be desired.

2. Key Issues

2.1 Error Susceptibility

Data compression, even the lossless approach, increases the impact of bit errors in the communication link. This is due to the increased information content per bit. For some approaches, this effect is further exacerbated by the interdependence of the bits in the reconstruction of the data. By choosing the right approach and adding channel coding to the communication link, the net effect of compression and error coding can be better data quantity and quality at the cost of additional system complexity.

2.2 Data System Considerations

Some of the potential benefits of data compression can only be realized if the data system is designed to exploit them. Lossless compression, for example, produces a variable volume output. To fully exploit the reduction in bits required to send the desired information, the data system would need to handle variable length packets and prioritized telemetry.

2.3 Operations Complexity

The capability to use data compression expands the trade space which can be considered during operations. While the additional capability may ease some operation problems, the additional decision complexity may add a burden.

2.4 Quality versus Quantity Tradeoff

Lossy compression introduces the option of increasing the volume of information which can be sent to the ground at the cost of adding distortion. NASA scientists cannot yet assess the impact of such trade-offs. Furthermore, this assessment is application dependent. Several lossy data compression schemes have been studied in academia and industry. One fact which has become clear is that the performance of a compression algorithm, in terms of reduction ratio versus quality, depends on the statistics of the data being compressed and the quality function appropriate to the application. Some schemes preserve edges and fine scale features, for instance, where others blur them or treat them as noise. Which approach is more satisfactory depends on the use to which the data will be put. While a distortion measure such as root mean square error is statistically precise, it is not always the appropriate measure of quality.

2.5 Experiment Design Considerations

Assuming that an instrument has been allocated a fixed bandwidth, designers are faced with several alternatives:

- a) Design an instrument incapable of exceeding the allocation,
- b) Design a more capable instrument, but use it only part of the time and provide rate buffering (duty cycling),
- c) Delete spatial or spectral components or decrease precision (editing),
- d) Accumulate data, lowering spatial, spectral or temporal resolution (integrating),
- e) Compress data in a manner which allows exact reconstruction (lossless compression),
- f) Compress data in a manner which introduces distortion (lossy compression),
- g) Reduce the data by on-board parameter or feature extraction (data processing).

Probably, a combination of the above techniques will give the best performance for the cost. The capability to perform on-board data processing or lossy compression is just now becoming a reality. Scientists have not yet considered what experiments might be enabled by combining these options with more powerful instruments.

2.6 Spacecraft Resource Considerations

Mass, power and volume are often scarce resources in spaceborne systems. While a single chip solution to lossless compression has been demonstrated, most compression schemes are more complex. At low rates, much can be accomplished by software on general purpose processors. The largest payoff, however, would come from compressing high-rate data. Many compression schemes appear straightforward enough to be implemented in a single chip or a small number of chips. This would reduce their use of spacecraft resources to an acceptable level.

2.7 Cost/Risk

While the non-recurring development cost and the recurring costs of including data compression on spacecraft may appear to be a barrier to doing so, this may be largely illusory. The cost per bit of information returned is significantly less than for many communications enhancements which NASA has funded over the years. (See Table 1.) Furthermore, the cost risk of adding compression is no greater than that of adding other new technologies. The performance risk for adding lossless compression is very low. The effects of lossless compression on the value of the returned data is well understood. For lossy compression of science data, however, the effect is not well understood in most cases. Lossy compression of operational data such as real time video and voice is much better understood and is being used commercially.

Table 1 gives cost/performance estimates for a number of improvements to the Deep Space Network (DSN). The unit of performance is a Big Aperture Performance Unit (BAPU), equivalent to one 70-meter antenna at 25 degrees Kelvin. Assuming that a 2:1 lossless compression were achieved, the effect would be equivalent to doubling the current capacity of 4.4 BAPUs. Experiments with data provided by the CRAF/Cassini and SIRTf projects and from the AVIRIS instrument have yielded lossless compression ratios ranging from 1.3:1 to 3.2:1, with 2:1 being a good conservative average if data are preconditioned to remove detector discrepancies.

Table 1. Performance versus Cost of Enhancement Techniques for the Deep Space Network*

TECHNIQUE	~BAPU gained	~COST \$M	\$M/BAPU
Upgrade all 3 64m to 70m	1.2	38	32.0
Array with VLA	2.0	20 (1st rental use)	10.0
Big Viterbi Decoder	1.6 (equiv.)	13	8.0
Compress all data 2:1	4.4 (equiv.)	5+3/mission	1.1
BWG and UNLAs on 70m	2.3	34+6	17.0
Ka-band and BWG on 70m	9.0 (equiv.)	27+10+5/mission	4.0

3. Solution Approaches

Several approaches to eliminating barriers to effective use of data compression were considered. The paragraphs below describe, not in priority order, those which the discussion group deemed most promising. Table 2 shows the issues which each approach would address.

3.1 Develop New Data Compression Techniques

While many data compression approaches are being explored commercially and in academia, NASA has several unique requirements which have not been fully addressed. High ratio compression would have a high payoff for remote experiment monitoring. Lossy compression which preserves science value could be important for a number of instruments, providing we could learn how to measure science value. Combining data compression (source coding) with error protection (channel coding) may yield more efficient use of communication and storage resources.

3.2 Improve Our Understanding of the Science Value of Compressed Data

Experimentally compressing realistic science data and determining the resultant effect on the analysis of these data would help to clarify and quantify the impact of proposed compression schemes. Studies examining the trade-offs involving more capable science instruments and observation/compression/analysis scenarios would help to clarify the alternatives for space and earth science observation.

* Data provided by Ivan Onyszchuk in memo 331-91.2-023 to Dan Erickson dated April 30, 1991

3.3 Develop Data System Designs and Operations Strategies for Data Compression

Variable length packets, optional prioritized telemetry, and event-responsive operations could allow the gains of on-board processing to be fully realized. Designs and demonstrations of such capabilities are needed to lower the risk of their incorporation into flight projects.

3.4 Develop Efficient Data Compression Hardware

To address the mass, power and volume constraints, data compression would best be implemented with application specific integrated circuits (ASICs). Flight qualifiable ASICs could be developed in the technology program for a few key compression techniques.

Table 2. Issues Versus Approaches for Compression Technology for Space to Earth Transmission

Approach Issue	New Techniques	Science Value Studies	System Approaches	Compression Hardware
Error Susceptibility	X		X	
System Considerations			X	
Operations Complexity			X	
Quality vs. Quantity Tradeoffs	X	X	X	
Experiment Design Considerations		X	X	
Spacecraft Resource Constraints				X
Cost/Risk			X	X

4. Specific Recommendations

The discussion group on data compression for space to earth transmission makes the following recommendations:

- 1) Data compression is a cost-effective way to improve communications and storage capacity. NASA should use lossless data compression wherever possible. NASA should continue working with the Consultative Committee for Space Data Systems to define lossless data compression standards, so that space qualified hardware can make maximum use of commonality.

- 2) NASA should conduct experiments and studies on the value and effectiveness of lossy data compression. These studies should include participation by key earth and space scientists who would evaluate the decrease of science value due to the distortions introduced and the increase in science value due to increased temporal, spectral, spatial and measurement resolution and increased coverage. These studies might best be funded jointly by codes S and R.
- 3) NASA should develop and select approaches to high-ratio compression of operational data such as voice and video.
- 4) NASA should develop data compression integrated circuits for a few key approaches identified in the preceding recommendations.
- 5) NASA should examine new data compression approaches such as combining source and channel encoding, where high-payoff gaps are identified in currently available schemes.
- 6) Users and developers of data compression technologies should be in closer communications within NASA and with academia, industry, and other government agencies. A data compression working group, newsletter, and/or electronic bulletin board should be considered.

Participants

The participants in this discussion group were Daniel E. Erickson, William G. Hartz, Dana Kloza, Trent Mills, Dmitry A. Novik, Ivan Onyszchuk, Christopher J. Pestak, Robert Stack, Jack Venebrux, Wayne Whyte, Jr., and Carol Wong. See the appendix for addresses.